

# STOP-STOP-HIGGS PRODUCTION AT FUTURE LINEAR COLLIDER

A. DJOUADI, J.-L. KNEUR<sup>a</sup> and G. MOULTAKA

*Physique Mathématique et Théorique, UMR No 5825-CNRS,  
Université Montpellier II, F-34095 Montpellier Cedex 5, France*

In the Minimal Supersymmetric Standard Model, the cross section for the associated production of the lightest neutral Higgs boson with the lightest top squark pairs can be rather substantial at high energies. We summarize the properties of this production process at a future  $e^+e^-$  linear collider, including the  $\gamma\gamma$  mode.

## 1 Introduction

In the Minimal Supersymmetric Standard Model (MSSM)<sup>1</sup>, if the mixing between third generation squarks is large, stops/sbottoms can be rather light<sup>2</sup> and at the same time, their coupling to Higgs bosons can become substantial. This might have a rather large impact on the phenomenology of the MSSM Higgs bosons<sup>3-7</sup>. More precisely, concentrating on scalar top quarks, their mass eigenvalues are given by

$$m_{\tilde{t}_{1,2}}^2 = m_t^2 + \frac{1}{2} \left[ m_{\tilde{Q}_L}^2 + m_{\tilde{t}_R}^2 + \dots \mp \sqrt{(m_{\tilde{Q}_L}^2 - m_{\tilde{t}_R}^2 + \dots)^2 + 4m_t^2 \tilde{A}_t^2} \right], \quad (1)$$

where  $m_{\tilde{Q}_L}$ ,  $m_{\tilde{t}_R}$  are the soft-SUSY breaking scalar masses and the dots stand for the  $D$ -terms  $\propto M_Z^2 \cos 2\beta$ . In the decoupling limit (the lightest  $h$  boson is Standard Model like and the other bosons  $A, H$  and  $H^\pm$ , are very heavy), the expressions of the coupling  $h\tilde{t}_1\tilde{t}_1$  simply reads ( $\theta_t$  is the mixing angle and  $s_W \equiv \sin \theta_W$ )

$$g_{h\tilde{t}_1\tilde{t}_1} = \cos 2\beta \left[ \frac{1}{2} \cos^2 \theta_t - \frac{2}{3} s_W^2 \cos 2\theta_t \right] + \frac{m_t^2}{M_Z^2} + \frac{1}{2} \sin 2\theta_t \frac{m_t \tilde{A}_t}{M_Z^2}. \quad (2)$$

Large values of  $\tilde{A}_t \equiv A_t - \mu/\tan \beta$  lead to  $g_{h\tilde{t}_1\tilde{t}_1} \sim \tilde{A}_t$  and to an almost maximal  $\tilde{t}$  mixing angle,  $|\sin 2\theta_t| \simeq 1$ , in particular if  $m_{\tilde{Q}_L} \simeq m_{\tilde{t}_R}$ . The measurement of this important coupling would open a window to probe directly some of the soft-SUSY breaking terms of the potential. To measure Higgs-squarks couplings directly, one needs to consider the three-body associated production of Higgs bosons with scalar quark pairs<sup>4-7</sup>. This is the supersymmetric analog to the processes of Higgs boson radiation from top quark lines<sup>8,9</sup> which allows to probe the  $t\bar{t}$ -Higgs Yukawa coupling directly. [At the LHC, the process  $pp \rightarrow t\bar{t}$ +Higgs<sup>8</sup> although not competitive with the gluon fusion mechanism<sup>10</sup>, can provide a complementary signal since backgrounds are smaller.]

Here, we report on the production of a light Higgs boson  $h$  in association with top squarks at future  $e^+e^-$  linear machines<sup>5</sup>, including the  $\gamma\gamma$  option, both in the unconstrained MSSM and minimal SUGRA cases. For simplicity, we work in the approximation of being close to the decoupling limit, which implies that we do

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<sup>a</sup>Speaker

not consider other Higgs production processes with e.g. the heavy  $H$  or  $A$  bosons produced in association with top squarks. For large masses, these processes will be suppressed by phase-space well before the decoupling regime is reached.

## 2 Associated production at $e^+e^-$ colliders

At future linear  $e^+e^-$  colliders, the final state  $\tilde{t}_1\tilde{t}_1h$  may be generated in three ways: (i) two-body production of a mixed pair of top squarks and the decay of the heaviest stop to the lightest one and a Higgs boson, (ii) the continuum production in  $e^+e^-$  annihilation  $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1h$  and (iii) the continuum production in  $\gamma\gamma$  collisions  $\gamma\gamma \rightarrow \tilde{t}_1\tilde{t}_1h$ .

### 2.1 Two-body production and decay

The total cross section<sup>11</sup> for the process (i) should, in principle, be large enough for the final state to be copiously produced. However,  $\sigma(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_2)$  involves the  $Z\tilde{t}_1\tilde{t}_2$  coupling, proportional to  $\sin 2\theta_t$ , while the  $|g_{h\tilde{t}_1\tilde{t}_2}|$  coupling in most of the parameter space is proportional to  $\cos 2\theta_t$ , such that the cross section times branching ratio will be very small in the no mixing  $[\theta_t \sim 0]$  and maximal mixing  $[|\theta_t| \sim \pi/4]$  cases. [In addition, the decay width  $\tilde{t}_2 \rightarrow h\tilde{t}_1$  is in general much smaller<sup>11</sup> than the  $\tilde{t}_2$  decay widths into chargino and neutralinos]. Nevertheless, there are regions of the MSSM parameter space where the combination  $\sin 2\theta_t \times \cos 2\theta_t$  can be large; this occurs typically for a not too small  $m_{\tilde{t}_L}-m_{\tilde{t}_R}$  splitting and moderate  $\tilde{A}_t$  values.<sup>5</sup> In this case, which is often realized in the mSUGRA scenario, this mechanism is visible for the expected high luminosities<sup>12</sup>  $\int \mathcal{L}dt \sim 500 \text{ fb}^{-1}$ .

This is illustrated in Fig. 1, where the cross section  $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_2$  times the branching ratio  $\text{BR}(\tilde{t}_2 \rightarrow \tilde{t}_1h)$  is shown as a function of the  $\tilde{t}_1$  mass at a c.m. energy of  $\sqrt{s} = 800 \text{ GeV}$ . We have chosen a mSUGRA scenario with  $\tan\beta = 30$ ,  $m_{1/2} = 100 \text{ GeV}$ ,  $A_0 = -600 \text{ GeV}$  and  $\text{sign}(\mu) = +$ . (The dotted lines show the contribution of the non-resonant process, discussed below, for the same input choice). The cross section can reach the level of 1 fb for relatively small  $m_{\tilde{t}_1}$  values, leading to thousand events in a few years, for  $\int \mathcal{L}dt \sim 500 \text{ fb}^{-1}$ .

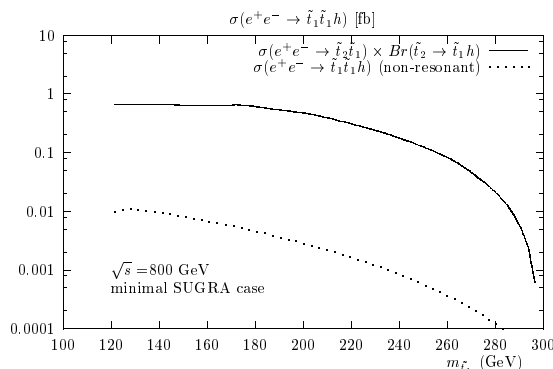


Figure 1: The production cross section  $\sigma(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1h)$  [in fb] as a function of  $m_{\tilde{t}_1}$  in the mSUGRA case;  $\tan\beta = 30$ ,  $m_{1/2} = 100 \text{ GeV}$  and  $A_0 = -600 \text{ GeV}$ .

## 2.2 Production in the continuum in $e^+e^-$ collisions

The cross section for the process  $e^+e^- \rightarrow \tilde{q}_i \tilde{q}_i^* \Phi$  with  $\Phi$  the CP-even Higgs boson  $h$  or  $H$ , and  $\tilde{q}_i$  any of the two squarks has been calculated in<sup>5</sup>. We show in Fig. 2 the rates for the  $\tilde{t}_1 \tilde{t}_1^* h$  final state as a function of the  $\tilde{t}_1$  mass in the unconstrained MSSM, at  $\sqrt{s} = 800$  GeV. For not too large  $\tilde{t}_1$  masses and large values of the parameter  $\tilde{A}_t$ , the production cross sections can exceed 1 fb, to be compared to the SM-like process  $e^+e^- \rightarrow t\bar{t}h$ <sup>9</sup> of the order of 2 fb for  $M_h \sim 130$  GeV. This provides more than one thousand events in a few years, with a luminosity  $\int \mathcal{L} dt \sim 500 \text{ fb}^{-1}$ , which should be sufficient to isolate the final state and measure  $g_{\tilde{t}_1 \tilde{t}_1^* h}$  with some accuracy.

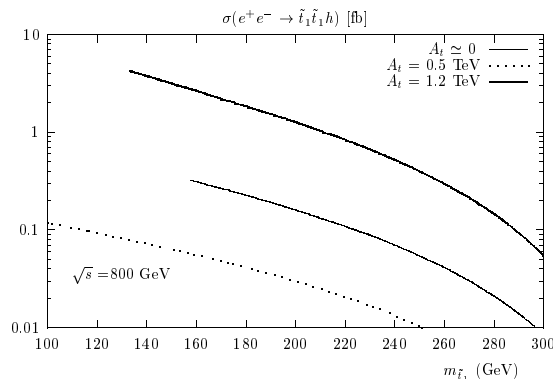


Figure 2: The cross section  $\sigma(e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1^* h)$  [in fb] as a function of the  $\tilde{t}_1$  mass and the choices  $\tan \beta = 30$ ,  $A_t = 0$  (0.5) TeV;  $\tan \beta = 3$ ,  $A_t = 1.2$  TeV (and  $\mu = -600$  GeV).

Note however that  $\tilde{A}_t$  cannot be arbitrarily large without conflicting present constraints: more precisely, the absence of charge and color breaking minima (CCB)<sup>13</sup> can put rather stringent bounds on  $\tilde{A}_t$ , and large  $\tilde{A}_t$  values also generate potentially large contributions to electroweak high-precision observables, in particular to the  $\rho$  parameter<sup>14</sup>, severely constrained by LEP1 data.<sup>15</sup> Those constraints, as well as the present experimental lower bounds on the top squark and Higgs boson masses, were systematically taken into account in our analysis. We observed that in the unconstrained MSSM case, the continuum production cross section in  $e^+e^-$  annihilation  $\sigma(e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1^* h)$  is often larger than the resonant cross section for the production of  $\tilde{t}_1 \tilde{t}_2$  and the subsequent 2-body decay  $\tilde{t}_2 \rightarrow \tilde{t}_1 h$ , but this is not generic. Indeed, in a situation where both a non-negligible  $m_{\tilde{t}_L} - m_{\tilde{t}_R}$  splitting and a moderate  $\tilde{A}_t$  occurs, provided there is sufficient phase space allowed, the production via a resonant  $\tilde{t}_2$  becomes competitive and even dominant, as illustrated in Fig. 1.

## 2.3 Production in the continuum in $\gamma\gamma$ collisions

Future high-energy  $e^+e^-$  linear colliders can be turned into high-energy  $\gamma\gamma$  colliders, with the high energy photons coming from Compton back-scattering of laser beams.<sup>16</sup> The c.m. energy of the  $\gamma\gamma$  collider is expected to be as much as  $\sim 80\%$  of the one of the original  $e^+e^-$  machine. However, the total luminosity is expected to be somewhat smaller than the one of the  $e^+e^-$  mode. The total cross section for the subprocess  $\gamma\gamma \rightarrow \tilde{t}_1 \tilde{t}_1^* h$ , calculated in<sup>5</sup>, is shown in Fig. 3 at a two-photon

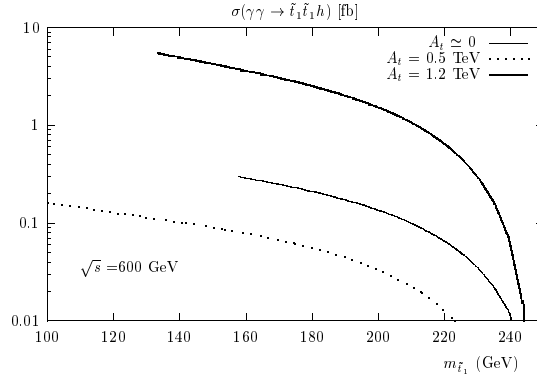


Figure 3:  $\sigma(\gamma\gamma \rightarrow \tilde{t}_1\tilde{t}_1h)$  [in fb] at  $\sqrt{s_{\gamma\gamma}} = 600$  GeV as a function of  $m_{\tilde{t}_1}$ . The other parameters have the same values as in Fig. 2.

c.m. energy  $\sqrt{s_{\gamma\gamma}} \lesssim 0.8\sqrt{s_{ee}} = 600$  GeV and as a function of the  $\tilde{t}_1$  mass, without convolution with the photon spectrum and with the same inputs and assumptions as in Fig. 2 to compare with the  $e^+e^-$  mode. Because the c.m. energy of the  $\gamma\gamma$  collider is only  $\sim 80\%$  of the one of the original  $e^+e^-$  machine, the process is of course less phase-space favored than in the  $e^+e^-$  mode. Nevertheless, the cross section for the  $\tilde{t}_1\tilde{t}_1h$  final state is of the same order as in the  $e^+e^-$  mode for c.m. energies not too close to the kinematical threshold, and the process might be useful to obtain complementary information since it does not involve the  $Z$ -boson and  $\tilde{t}_2$  exchanges. If the luminosities of the  $\gamma\gamma$  and  $e^+e^-$  colliders are comparable, a large number of events might be collected for small stop masses and large  $\tilde{A}_t$  values.

#### 2.4 Decay modes and signal

Top squarks in the mass range discussed above will mainly decay<sup>11</sup> into a  $c$  quark + neutralino,  $\tilde{t}_1 \rightarrow c\chi_1^0$ , or a  $b$  quark + chargino,  $\tilde{t}_1 \rightarrow b\chi_1^+$ . In this latter case the lightest chargino,  $\chi_1^+$  will decay into the LSP and a real or virtual  $W$  boson, leading to the same topology as in the case of the top quark decay, but with a large amount of missing energy due to the undetected LSP (three and four-body decays<sup>17</sup> of the stop are also possible with the same topology). At  $e^+e^-$  colliders one can use the dominant decay mode of the lightest Higgs boson,  $h \rightarrow b\bar{b}$ . The final state topology will then consist of  $4b$  quarks, two of them peaking at an invariant mass  $M_h$ , two real (or virtual)  $W$ 's and missing energy. With efficient micro-vertex detectors, this final state should be rather easy to detect.

### 3 Conclusions

At  $e^+e^-$  colliders with c.m. energies  $\sqrt{s} \gtrsim 500$  GeV and with very high luminosities  $\int \mathcal{L} dt \sim 500 \text{ fb}^{-1}$ , the process  $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1h$  can lead to several hundreds of events, since the cross sections can exceed the level of a 1 fb for not too heavy top squarks and large trilinear coupling,  $\tilde{A}_t \gtrsim 1$  TeV. In the case where the top squark decays into a  $b$  quark and a real/virtual chargino, the final state topology with  $4b$  quarks, missing energy and additional jets or leptons will be rather spectacular and should be easy to be seen experimentally, thanks to the clean environment of these colliders.

In the  $\gamma\gamma$  option of the  $e^+e^-$  collider, the cross sections are similar as previously far from the particle thresholds, but are suppressed for larger masses because of the reduced c.m. energies; for  $\gamma\gamma$  luminosities of the same order as the original  $e^+e^-$  luminosities, the  $\tilde{t}_1\tilde{t}_1h$  final state should also be observable in this mode, at least in some areas of the MSSM parameter space.

The production cross section of the  $\tilde{t}_1\tilde{t}_1h$  final state is directly proportional to the square of the  $\tilde{t}_1\tilde{t}_1h$  couplings, therefore studying this process will allow to measure this important coupling and to probe directly some of the soft-SUSY breaking parameters.

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